

How tightly is nuclear symmetry energy constrained by unitary Fermi gas?

Nai-Bo Zhang,^{1,2} Bao-Jun Cai,^{1,3,4} Bao-An Li,¹ William G. Newton,¹ and Jun Xu⁵

¹*Department of Physics and Astronomy, Texas A&M University-Commerce, Commerce, TX 75429, USA*

²*Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, Institute of Space Sciences, Shandong University, Weihai 264209, China*

³*Department of Physics, Shanghai University, Shanghai 200444, China*

⁴*Department of Physics and Astronomy and Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai 200240, China*

⁵*Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*

(Dated: April 11, 2017)

Using the same approach proposed by Kolomeitsev *et al* in their recent work [1], we examine how tightly the nuclear symmetry energy $E_{\text{sym}}(\rho)$ at density ρ is constrained by the universal equation of state (EOS) of the unitary Fermi gas $E_{\text{UG}}(\rho)$, taking into account the higher order skewness parameters J_0 and J_{sym} and reexamining the uncertainty in K_{sym} . We found that $E_{\text{UG}}(\rho)$ does provide a useful lower boundary for the $E_{\text{sym}}(\rho)$ confirming the finding by Kolomeitsev *et al*. However, it does not tightly constrain the correlation between the magnitude $E_{\text{sym}}(\rho_0)$ and slope L unless the curvature K_{sym} of the symmetry energy at saturation density ρ_0 is more precisely known within its current uncertain range. Most of the $E_{\text{sym}}(\rho)$ functionals previously excluded by the $E_{\text{UG}}(\rho)$ assuming $K_{\text{sym}} = 0$ in ref. [1] may be restored considering the currently known uncertainties of the K_{sym} . The large uncertainty in the skewness parameters affects the $E_{\text{sym}}(\rho_0)$ versus L correlation by the same almost as significantly as the uncertainty in K_{sym} .

PACS numbers: 24.30.Cz, 21.65.+f, 21.30.Fe, 24.10.Lx

Introduction: To understand the nature of neutron-rich nucleonic matter has been a major scientific goal in both nuclear physics and astrophysics. The density dependence of nuclear symmetry energy $E_{\text{sym}}(\rho)$ has been a major uncertain part of the equation of state (EOS) of neutron-rich matter especially at high densities, see, e.g., collections in [2]. Reliable knowledge about the $E_{\text{sym}}(\rho)$ has significant ramifications in answering many interesting questions regarding the structure of rare isotopes and neutron stars, dynamics of heavy-ion collisions and supernova explosions as well as the frequency and strain amplitude of gravitational waves from deformed pulsars and/or cosmic collisions involving neutron stars. During the last two decades, significant efforts have been devoted to exploring the $E_{\text{sym}}(\rho)$ using both terrestrial laboratory experiments [3–13] and astrophysical observations [14–21]. Extensive surveys of the extracted constraints on the $E_{\text{sym}}(\rho)$ around the saturation density ρ_0 indicate that the central values of the $E_{\text{sym}}(\rho_0)$ and its slope $L = [3\rho(\partial E_{\text{sym}}/\partial \rho)]_{\rho_0}$ scatter around 31.6 MeV and 58.9 MeV, respectively [15, 22, 23]. At densities away from ρ_0 , however, the $E_{\text{sym}}(\rho)$ remains rather unconstrained especially at supra-saturation densities [13].

Interestingly, recent progresses in another seemingly different field may provide additional information about the density dependence of nuclear symmetry energy. Indeed, theoretical and experimental studies of cold atoms have made impressive progress in recent years, see, e.g., refs. [24–27] for recent reviews, providing reliable information about the universal EOS (E_{UG}) of unitary Fermi gas interacting via pairwise s -waves with infinite scattering length but zero effective range. The universal E_{UG} constrains stringently the EOS of pure neutron matter

(PNM) at sub-saturation densities, thus provides possibly additional constraints on the nuclear symmetry energy. In fact, it was recently conjectured that the E_{UG} provides the lower boundary of the EOS of PNM (E_{PNM}), namely, $E_{\text{UG}} \geq E_{\text{PNM}}$ [1]. Moreover, using a set of known parameters of symmetric nuclear matter (SNM), and taking zero as an upper bound on the curvature $K_{\text{sym}} = [9\rho^2(\partial^2 E_{\text{sym}}(\rho)/\partial \rho^2)]_{\rho_0}$ of $E_{\text{sym}}(\rho)$ at ρ_0 , the authors of ref. [1] obtained a region of $E_{\text{sym}}(\rho_0)$ - L space that is inconsistent with the unitary gas constraints, excluding many $E_{\text{sym}}(\rho)$ functionals currently actively used in both nuclear physics and astrophysics.

The derivation of the excluded region in $E_{\text{sym}}(\rho_0)$ - L space by ref. [1] relies on two assumptions which the authors refer to as conservative: (i) that terms in the density expansion of the nuclear matter EOS of 3rd order and higher can be neglected, and that (ii) $K_{\text{sym}} \leq 0$. The results they obtain are sensitive to these assumptions, and given the important ramifications of the findings in ref. [1], we are motivated to critically examine them using the same approach. In this paper, we include the third-order terms in density characterized by the skewness coefficients $J_0 = 27\rho_0^3 \partial^3 E_0(\rho)/\partial \rho^3|_{\rho=\rho_0}$ and $J_{\text{sym}} = 27\rho_0^3 \partial^3 E_{\text{sym}}(\rho)/\partial \rho^3|_{\rho=\rho_0}$ in expanding the $E_0(\rho)$ and $E_{\text{sym}}(\rho)$, respectively. Particularly, we carefully examine the uncertainties of the curvature K_{sym} of the symmetry energy and the skewness coefficients J_0 and J_{sym} , taking into account energy density functionals that are consistent with the PNM EOS derived from microscopic calculations, and examine the effects of those uncertainties on the region of $E_{\text{sym}}(\rho_0)$ - L space excluded by the unitary gas constraints.

While Skyrme models consistent with microscopic

PNM calculations tend to give K_{sym} in the range -100 to -200 MeV [31, 34], Relativistic Mean Field (RMF) models consistent with microscopic PNM calculations can give positive values of K_{sym} [30, 31], reflecting a difference in the form of these two classes of energy density functionals. Indeed, some reputable non-relativistic and relativistic energy density functionals in the literature, see, e.g., reviews in ref. [28–30, 32], predict positive K_{sym} values and meet all existing constraints including the EOS of PNM within their known uncertain ranges. For example, the TM2 RMF interaction has $K_{\text{sym}} = 50$ MeV and passes the PNM test of ref.[30]. To our best knowledge, while the majority of existing models predict negative values for K_{sym} , there is no fundamental physics principle excluding positive K_{sym} values. The current situation clearly calls for more studies on the K_{sym} especially its experimental constraints. Hopefully, ongoing experiments at several laboratories [33] to extract the isospin dependence of nuclear incompressibility and subsequently the K_{sym} from giant resonances of neutron-rich nuclei will help settle the issue in the near future.

The lower boundary of nuclear symmetry energy constrained by the universal EOS of unitary Fermi gas: Within the parabolic approximation for the EOS of isospin asymmetric nuclear matter (ANM) in terms of the energy per nucleon E , i.e., $E(\rho, \delta) = E_0(\rho) + E_{\text{sym}}(\rho)\delta^2 + \mathcal{O}(\delta^4)$, the symmetry energy $E_{\text{sym}}(\rho) = 2^{-1}[\partial^2 E(\rho, \delta)/\partial \delta^2]_{\delta=0}$ can be approximated by

$$E_{\text{sym}}(\mu) \approx E_{\text{PNM}}(\mu) - E_0(\mu), \quad (1)$$

where $\mu = \rho/\rho_0$ is the reduced density and $\delta = (\rho_n - \rho_p)/\rho$ is the isospin asymmetry of ANM. Using the conjecture $E_{\text{PNM}}(\rho) \geq E_{\text{UG}}(\rho)$ [1] and the EOS of unitary gas

$$E_{\text{UG}}(\mu) = \frac{3\hbar^2 k_F^2}{10m_n} \xi \equiv E_{\text{UG}}^0 \mu^{2/3} \quad (2)$$

where k_F is the neutron Fermi momentum and ξ is the Bertsch parameter [24–27], the lower boundary of symmetry energy can be obtained from

$$E_{\text{sym}}(\mu) \geq E_{\text{UG}}(\mu) - E_0(\mu) = E_{\text{UG}}^0 \mu^{2/3} - E_0(\mu). \quad (3)$$

The EOS of SNM around ρ_0 can be expended to the third order in density as

$$E_0(\mu) = E_0(\rho_0) + \frac{K_0}{18}(\mu-1)^2 + \frac{J_0}{162}(\mu-1)^3 + \mathcal{O}[(\mu-1)^4] \quad (4)$$

in terms of the incompressibility K_0 and skewness J_0 . At the saturation point of SNM, we adopt $E_0(\rho_0) = -15.9$ MeV and $\rho_0 = 0.164 \text{ fm}^{-3}$ [34]. The lower boundary of $E_{\text{sym}}(\rho)$ thus depends on the values of K_0 , J_0 and ξ .

The incompressibility K_0 of SNM has been extensively investigated [32, 35], and the most widely used values are

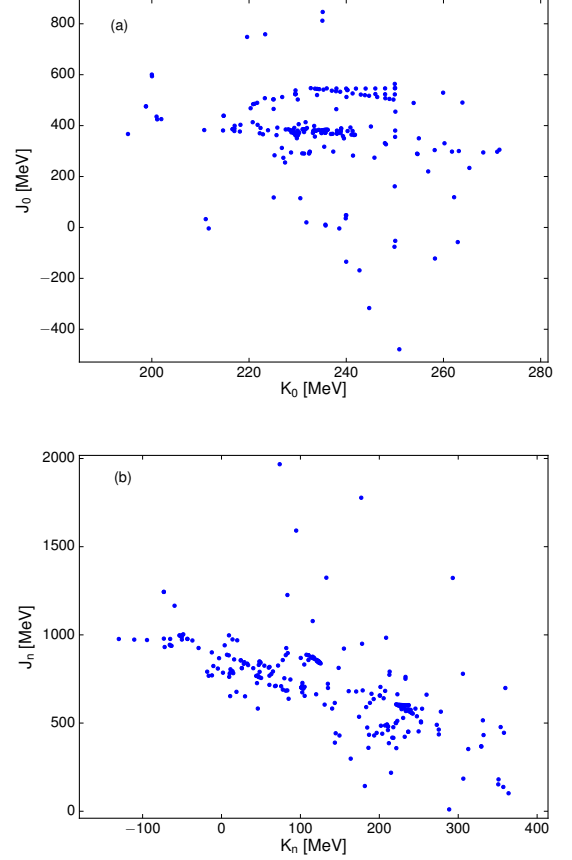


FIG. 1. The skewness parameter J_0 versus the incompressibility K_0 for symmetric matter (a) and the total curvature parameter $K_n = K_0 + K_{\text{sym}}$ versus the total skewness parameter $J_n = J_0 + J_{\text{sym}}$ (b) for all 173 Skyrme and 101 RMF models examined by Dutra *et al* [29, 30] which pass their pure neutron matter constraints and satisfy $190 < K_0 < 270$ MeV.

$K_0 = 240 \pm 20$ MeV [36, 37] or 230 ± 40 MeV [38]. However, the skewness coefficient J_0 is still poorly known [39–44]. In Fig. 1(a), we show K_0 and J_0 from 274 parameterizations of the Skyrme and RMF models that pass the PNM tests of Dutra *et al* [29, 30] and satisfy $K_0 = 230 \pm 40$ MeV. The spread in values for J_0 is very large, covering the range $\approx -400 < J_0 < 800$ MeV.

As reviewed recently in refs. [1, 27], currently the best estimate for the Bertsch parameter ξ from lattice Monte Carlo studies is $\xi = 0.372(5)$ consistent with the most accurate experimental value of $\xi = 0.376(4)$. Nonetheless, its values from various other models and experiments have scattered between 0.279 and 0.449(9) within the last decade.

Firstly, to show how the progress in pinning down the ξ has helped narrow down the lower boundary of the symmetry energy, shown in Fig. 2 with the red dashed lines are the variation of $E_{\text{sym}}(\rho)$ with $\xi = 0.37 \pm 0.1$, $J_0 = 0$ and $K = 230$ MeV. It is seen that effects of varying the ξ value are large especially at high densities.

Secondly, effects of the skewness parameter are shown by varying the value of J_0 between -400 MeV and 800 MeV, the range covered by the models plotted in Fig. 1(a). Although the range is very large, it translates to a range of uncertainty for $E_{\text{sym}}(\rho)$ that is equivalent to the range of uncertainty in K_0 (80 MeV). This is easy to understand as the expansion of SNM's EOS converges quickly around the normal density by design (the J_0 contribution of $J_0/162$ is a factor of 9 less than the $K_0/18$ term).

Considering the uncertainties of all relevant parameters involved, the most conservative lower boundary of $E_{\text{sym}}(\rho)$ shown as the shadowed region in Fig. 2 is obtained by using $\xi = 0.27$, $\rho_0 = 0.157 \text{ fm}^{-3}$, $E_0(\rho_0) = -15.5$ MeV, and $K_0 = 270$ MeV; for $\mu \leq 1$, $J_0 = -400$ MeV and for $\mu > 1$, $J_0 = 800$ MeV. Overall, our observations and results are consistent with the findings by Kolomeitsev *et al.* in ref. [1].

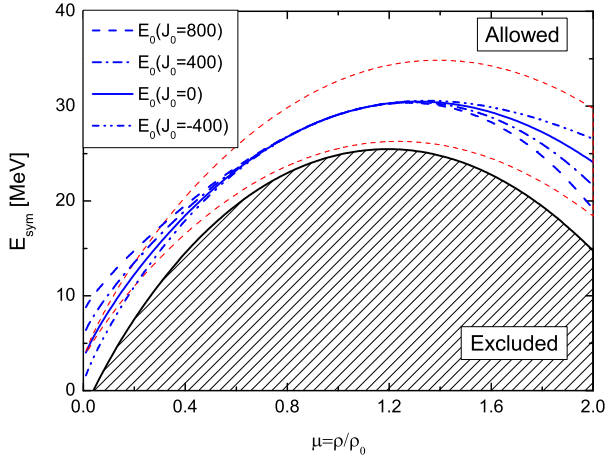


FIG. 2. The lower boundary of symmetry energy as a function of density for different skewness coefficients $J_0 = -400, 0, 400$, and 800 MeV. The red dashed region represents the variation of $E_{\text{sym}}(u)$ with $K_0 = 230$ MeV and $J_0 = 0$ MeV by adopting $\xi = 0.37 \pm 0.1$. The shadowed region shows the excluded region after considering the uncertainties of ξ , K and J_0 .

Constraining the $E_{\text{sym}}(\rho_0)$ versus L boundary: The symmetry energy $E_{\text{sym}}(\mu)$ can be expanded around ρ_0 to third order in density as

$$E_{\text{sym}}(\mu) = E_{\text{sym}}(\rho_0) + \frac{L}{3}(\mu - 1) + \frac{K_{\text{sym}}}{18}(\mu - 1)^2 + \frac{J_{\text{sym}}}{162}[(\mu - 1)^3] + \mathcal{O}[(\mu - 1)^4] \quad (5)$$

in terms of its magnitude $E_{\text{sym}}(\rho_0)$, slope L , curvature K_{sym} and skewness J_{sym} at ρ_0 . Inserting the above equation into Eq. (3), the lower boundary of $E_{\text{sym}}(\rho_0)$ can be expressed as

$$E_{\text{sym}}(\rho_0) \geq E_{\text{UG}}^0 \mu^{2/3} - E_0(\rho_0) - \frac{L}{3}(\mu - 1) - \frac{K_n}{18}(\mu - 1)^2 - \frac{J_n}{162}(\mu - 1)^3 \quad (6)$$

where $K_n = K_{\text{sym}} + K_0$ and $J_n = J_{\text{sym}} + J_0$. Taking the derivative of the above equation with respect to density on both sides, one can readily get an expression for the lower boundary of L

$$L = \frac{2E_{\text{UG}}^0}{\mu^{1/3}} - \frac{K_n}{3}(\mu - 1) - \frac{J_n}{18}(\mu - 1)^2. \quad (7)$$

Then, putting the above expression back to Eq. (6) the latter can be rewritten as

$$E_{\text{sym}}(\rho_0) \geq \frac{E_{\text{UG}}^0}{3\mu^{1/3}}(\mu + 2) + \frac{K_n}{18}(\mu - 1)^2 + \frac{J_n}{81}(\mu - 1)^3 - E_0(\rho_0). \quad (8)$$

These two equations reveal the correlation between the $E_{\text{sym}}(\rho_0)$ and L along their lower boundaries through the arbitrary density μ . Setting $J_n = 0$, the Eqs. (7) and (8) reduce exactly to the parametric equations of $E_{\text{sym}}(\rho_0)$ and L derived slightly differently in ref. [1]. We note that the quantities that determine the boundary of allowed values of $E_{\text{sym}}(\rho_0)$ and L are the total curvature parameter K_n and total skewness parameter J_n .

While having noted that K_{sym} is experimentally and theoretically poorly known, the $E_{\text{sym}}(\rho_0)$ versus L correlation along their boundaries was obtained in ref. [1] by setting $K_{\text{sym}} = 0$ based on the prediction of a chiral effective field theory. It was found that the resulting correlation excludes many of the currently actively used models for $E_{\text{sym}}(\rho)$. We reexamine this correlation by varying the ξ , J_n and K_{sym} within their known uncertain ranges. Again, the value of ξ is now well settled around 0.37. By varying it in its historical range of $\xi = 0.37 \pm 0.1$ we show the importance of knowing its precise value. Taking $K_{\text{sym}} = 0$, $J_n = 0$ and $K_0 = 230$ MeV, the two red dashed lines obtained with $\xi = 0.37 \pm 0.1$ in both (a) and (b) of Fig. 3 show the resulting lower boundaries of the $E_{\text{sym}}(\rho_0)$ versus L correlation.

The skewness coefficients J_0 and J_{sym} in J_n are both poorly known. We show in Fig 1(b) values of J_n against K_n for the 275 Skyrme and RMF models. J_n varies approximately in the range $0 \text{ MeV} \leq J_n \leq 2000 \text{ MeV}$. To our best knowledge, there is no experimental constraint available on this quantity. K_n varies approximately in the range $-150 \text{ MeV} \leq K_n \leq 370 \text{ MeV}$. Most of this comes from the big uncertainties in determining the value of K_{sym} , which are discussed in detail in ref. [13]. This is partially because the K_{sym} depends on not only L but also its derivative $(dL/d\rho)_{\rho_0}$ by definition. Microscopically, it depends on not only the nucleon isoscalar effective mass m_0^* and neutron-proton effective mass splitting $m_n^* - m_p^*$ but also their momentum and density dependences that are all essentially completely unknown [13]. The latest calculations within many Skyrme Hartree-Fock and/or relativistic mean-field models indicate that $-400 \leq K_{\text{sym}} \leq 100 \text{ MeV}$ [28–30, 32].

transition point [45]. Thus, astrophysical observations of neutron stars can potentially constrain the J_0 *albeit* probably not before other EOS parameters are well determined. On the other hand, in terrestrial laboratory experiments, there have been continued efforts to determine the K_{sym} [32]. One outstanding example is the measurement of the isospin dependence of nuclear incompressibility $K(\delta) \approx K_0 + K_\tau \delta^2 + \mathcal{O}(\delta^4)$ where $K_\tau = K_{\text{sym}} - 6L - J_0 L/K_0$ using giant resonances of neutron-rich nuclei [46, 47]. While the current estimate of $K_\tau \approx -550 \pm 100$ MeV [32] from analyzing many different kinds of terrestrial experiments is still too rough to constrain tightly the individual values of J_0 and K_{sym} , new experiments with more neutron-rich beams have the promise of improving significantly the accuracy of the measured K_τ [33]. Thus, we are hopeful that not only the zeroth and first-order parameters K_0 , $E_{\text{sym}}(\rho_0)$ and L but also high-order coefficients J_0 and K_{sym} can be pinned down in the near future by combining new analyses of upcoming astrophysical observations and terrestrial experiments.

Acknowledgements: We would like to thank Umesh Garg for helpful communications. NBZ is supported in part by the China Scholarship Council. BAL acknowledges the U.S. Department of Energy, Office of Science, under Award Number DE-SC0013702, the CUSTIPEN (China-U.S. Theory Institute for Physics with Exotic Nuclei) under the US Department of Energy Grant No. DE-SC0009971 and the National Natural Science Foundation of China under Grant No. 11320101004. JX is supported in part by the Major State Basic Research Development Program (973 Program) of China under Contract Nos. 2015CB856904 and 2014CB845401, the National Natural Science Foundation of China under Grant Nos. 11475243 and 11421505, the “100-talent plan” of Shanghai Institute of Applied Physics under Grant Nos. Y290061011 and Y526011011 from the Chinese Academy of Sciences, the Shanghai Key Laboratory of Particle Physics and Cosmology under Grant No. 15DZ2272100, and the Shanghai Pujiang Program under Grant No. 13PJ1410600.

-
- [1] E. E. Kolomeitsev, J. M. Lattimer, A. Ohnishi, and I. Tews, arXiv:1611.07133v1 (2016).
 - [2] Topical Issue on Nuclear Symmetry Energy, Eds: B.A. Li, A. Ramos, G. Verde and I. Vidana, Euro Phys. Journal **A50**, No. 2 (2014).
 - [3] B. A. Li, C.M. Ko and W. Bauer, *Int. J. Mod. Phys. E* **7**, 147 (1998).
 - [4] *Isospin Physics in Heavy-Ion Collisions at Intermediate Energies*, Eds. B. A. Li and W. Udo Schröder (Nova Science Publishers, Inc, New York, 2001)
 - [5] V. Baran, M. Colonna, V. Greco and M. Di Toro, *Phys. Rep.* **410**, 335 (2005).
 - [6] B.A. Li, L.W. Chen and C.M. Ko, *Phys. Rep.* **464**, 113 (2008).
 - [7] W. G. Lynch, M. B. Tsang, Y. Zhang, P. Danielewicz, M. Famiano, Z. Li and A. W. Steiner, *Prog. Nucl. Part. Phys.* **62**, 427 (2009).
 - [8] P. Danielewicz and J. Lee, *Nucl. Phys.* **A818**, 36 (2009).
 - [9] W. Trautmann and H. H. Wolter, *Int. J. Mod. Phys. E* **21**, 1230003 (2012).
 - [10] M. B. Tsang, J. R. Stone, F. Camera, P. Danielewicz, S. Gandolfi, K. Hebeler, C. J. Horowitz, Jenny Lee, W. G. Lynch, Z. Kohley, R. Lemmon, P. Moller, T. Murakami, S. Riordan, X. Roca-Maza, F. Sammarruca, A. W. Steiner, I. Vidana and S. J. Yennello, *Phys. Rev. C* **86**, 015803 (2012).
 - [11] C. J. Horowitz, E. F. Brown, Y. Kim, W. G. Lynch, R. Michaels, A. Ono, J. Piekarewicz, M. B. Tsang, H. H. Wolter, *J. of Phys. G* **41**, 093001 (2014).
 - [12] M. Baldo and G. F. Burgio, *Progress in Particle and Nuclear Physics* **91**, 203 (2016).
 - [13] B.A. Li, arXiv:1701.03564, *Nuclear Physics News* (2017) to appear.
 - [14] A. W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, *Phys. Rep.* **411**, 325 (2005).
 - [15] J.M. Lattimer, *Annu. Rev. Nucl. Part. Sci.* **62**, 485 (2012).
 - [16] W.G. Newton et al., *Euro Phys. J.* **A50**, 41 (2014).
 - [17] K. Iida and K. Oyamatsu, *Euro Phys. J.* **A50**, 42 (2014).
 - [18] J.M. Pearson, N. Chamel, A.F. Fantina and S. Goriely, *Euro Phys. J.* **A50**, 43 (2014).
 - [19] F.J. Fattoyev, W.G. Newton and B.A. Li, *Euro Phys. J.* **A50**, 44 (2014).
 - [20] T. Fischer, M. Hempel, I. Sagert, Y. Suwa and J. Schaffner-Bielich, *Euro Phys. J.* **A50**, 45 (2014).
 - [21] D. Blaschke, D. E. Alvarez-Castillo and T. Klähn, arXiv:1604.08575.
 - [22] B.A. Li and X. Han, *Phys. Lett. B* **727**, 276 (2013).
 - [23] M. Oertel, M. Hempel, T. Klähn, S. Typel, arXiv:1610.03361.
 - [24] M. W. Zwiernlein, in *Novel Superfluids vol. 2*, ed. K.-H. Bennemann and J. B. Ketterson (Oxford), Ch. 18 (2015).
 - [25] M. J. H. Ku, A. T. Sommer, L. W. Cheuk and M. W. Zwiernlein, *Science* **335**, 563 (2012).
 - [26] G. Zuñi, T. Lompe, A. N. Wenz, S. Jochim, P. S. Julienne and J. M. Hutson, *Phys. Rev. Lett.* **110**, 135301 (2013).
 - [27] M. G. Endres, D. B. Kaplan, J. W. Lee, and A. N. Nicholson, *Phys. Rev. A* **87**, 023615 (2013).
 - [28] L.W. Chen, B.J. Cai, C.M. Ko, B.A. Li, C. Shen and J. Xu, *Phys. Rev. C* **80**, 014322 (2009).
 - [29] M. Dutra, O. Loureno, J. S. S Martins, A. Delfino, J. R. Stone and P. D. Stevenson, *Phys. Rev. C* **85**, 035201 (2012).
 - [30] M. Dutra, O. Loureno, S. S. Avancini, B. V. Carlson, A. Delfino, D. P. Menezes, C. Providencia, S. Typel and J. R. Stone, *Phys. Rev. C* **90**, 055203 (2014).
 - [31] F. Fattoyev, W.G. Newton, J. Xu and B.A. Li, *Phys. Revs. C* **86** 025804, (2012)
 - [32] G. Colò, U. Garg, and H. Sagawa, *Eur. Phys. J. A* **50**, 26 (2014).
 - [33] Umesh Garg and Yiuwing Lui, private communications.
 - [34] B. A. Brown and A. Schwenk, *Phys. Rev. C* **89**, 011307 (2014).

- (2014) Erratum: [Phys. Rev. C **91**, 049902 (2015)].
- [35] J. R. Stone, N. J. Stone, and S. A. Moszkowski, Phys. Rev. C **89**, 044316 (2014).
 - [36] S. Shlomo, V. M. Kolomietz and G. Colo Eur. Phys. J. A **30**, 23 (2006).
 - [37] J. Piekarewicz, J. Phys. G **37**, 064038 (2010).
 - [38] E. Khan, J. Margueron, and I. Vidana, Phys. Rev. Lett. **109**, 092501 (2012).
 - [39] M. Meixner, J. P. Olson, G. Mathews, N. Q. Lan, and H. E. Dalhed, arXiv:1303.0064 (2013).
 - [40] L. W. Chen, Sci. China: Phys. Mech. Astron. 54, **s124** (2011).
 - [41] M. Farine, J. M. Pearson, and F. Tondeur, Nucl. Phys. **A615**, 135 (1997).
 - [42] T. Klähn et al., Phys. Rev. C 74, 035802 (2006).
 - [43] K. A. Maslov, E. E. Kolomeitsev, and D. N. Voskresensky, Nucl. Phys. **A950**, 64 (2016).
 - [44] B. J. Cai and L. W. Chen, arXiv:1402.4242v1 (2014).
 - [45] N.B. Zhang et al, in preparation (2017).
 - [46] T. Li et al., Phys. Rev. Lett. **99**, 162503 (2007).
 - [47] J. Piekarewicz, Phys. Rev. C **76**, 031301 (2007).